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AN EXPERIMENTAL DESIGN FOR LABORATORY SIMULATION OF PERIGLACIAL SOLIFLUCTION PROCESSES

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ABSTRACT

An experimental slope of gradient 12° was constructed, comprising two 5 m × 2 m × 0·3 m contiguous strips of natural soils. Soil freezing and thawing took place from the surface downwards in an open hydraulic system, water being supplied at the base of each soil. Thermal conditions, porewater pressures and soil displacements were monitored using a PC-based logging system, with readings taken at half-hourly intervals. Soil surface displacements due to frost heave and solifluction were measured using linear voltage displacement transducers. Soil temperatures were determined using thermistors and semiconductor temperature sensors. Antifreeze-filled miniature ceramic-tipped pressure transducers were used to determine porewater pressure variations. The potential of this experimental approach for precise monitoring of mass movement processes associated with thawing of ice-rich soils is demonstrated.

KEY WORDS periglacial; solifluction; experimental design; laboratory simulation

INTRODUCTION

The importance of gelifluction and frost creep in a wide range of periglacial environments has been demonstrated by numerous field studies (e.g. Washburn, 1979; Harris, 1987; Lewkowicz, 1988; Smith, 1988). Gelifluction is associated with annual thawing of ice-rich frozen ground, leading to high soil water contents during the thaw period. It is generally assumed that thaw consolidation causes the development of elevated porewater pressures and reduced frictional strength (Morgenstern and Nixon, 1971; McRoberts, 1978; Harris, 1981). Soils with low plasticity have been shown to respond by slow saturated downslope flowage (Hutchinson, 1991). Frost creep results from expansion of the soil during freezing followed by thaw-induced resettlement that causes gravitational downslope displacement of the soil mass (Washburn, 1979). Frost creep always accompanies gelifluction, but in drier sites may take place in the absence of saturated flow.

Such general relationships are well established, but field studies have not as yet provided the necessary precision of monitoring or experimental control to enable a more detailed exploration of the mechanisms of periglacial mass movement. An alternative approach is the simulation of periglacial slope processes whereby a slope is constructed in the laboratory and subjected to a controlled thermal and hydraulic regime. Such laboratory experimentation not only has the advantage of allowing greater precision and detail of monitoring but, by reducing the annual cycle of freezing and thawing to a few weeks, it also allows rapid simulation of the equivalent of many years' soil movement over a period of only a few months (Harris *et al.*, 1993). Previous experimentation has, however, tended to explore the style of soil displacement and its

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relationship to soil ice contents and soil properties (e.g. Rein and Burrous, 1980; Coutard *et al.*, 1988; Harris, 1983; Harris *et al.*, 1993) rather than monitor in detail such factors as the rate and timing of thaw, the rate and timing of thaw consolidation and relationships between thaw-induced porewater pressures and initiation and duration of downslope soil movement. This paper describes an experimental design for large-scale physical modelling to measure and record the timing and rate of: (a) frost penetration; (b) surface frost heaving; (c) thaw penetration; (d) porewater pressure changes; and (e) downslope surface soil displacement. It also presents some preliminary results to illustrate the value of the resulting data.

THE EXPERIMENTAL SLOPE

Harris *et al.* (1993) have described an earlier simulation of gelifluction and frost creep in which the response of four contrasting soil types to freezing and thawing from the surface downwards was compared. Although significant contrasts in the susceptibility of these soils to periglacial mass movement were demonstrated, detailed measurements of process variables were not made. The present study seeks to make such measurements, concentrating particularly on the monitoring of soil freezing and thawing, associated frost heaving and thaw consolidation, and porewater pressure changes. The experimental slope was constructed in a refrigerated container 5 m square and 1·1 m deep at the CNRS Centre de Géomorphologie in Caen, France. The present simulation follows a similar basic slope geometry to that adopted earlier, but incorporates a range of new instrumentation together with automatic PC-based data logging.

A slope base template of gradient 12° was constructed from compacted loam, and above this a 100 mm thick layer of coarse sand formed a basal drainage layer, connected to a metered water supply at the slope crest and a drain at the slope foot (Figure 1). Two 5 m × 2 m × 0·3 m contiguous strips of natural soil were then laid over the sand base (Figure 1). Thus, slope processes affecting two soils with somewhat different granulometry and geotechnical properties could be explored. The soils were collected from fresh quarry faces in western Normandy and represent the natural weathering products of Precambrian slate from Vire and Ordovician mudstone from Feuguerolles. The former soil is well graded and consists of a sandy silt, while the latter is less well graded, consisting of a gravelly silty fine sand. Soil properties are shown in Table I.

Prior to emplacement, each soil was thoroughly disaggregated and mixed using a cement mixer. Layers were added gradually, hand compacted using a wooden tamper and the interfaces between layers raked to ensure that no discontinuities were formed along which preferential ice segregation might occur. A double strip of polythene, with juxtaposed faces lubricated with silicon oil, was placed between the adjacent experimental slope sections and between each section and the outer confining gravel baffles (Figure 1). No lateral water migration between soils was therefore possible, and friction along the edges of each experimental soil strip was minimized, thus modelling an infinite slope more accurately. During the experimental programme, no attempt was made to remove soil accumulating at the base of the slope, nor to replace soil moving away from the head of the slope, so that the upper and lower slope boundary conditions changed slightly. However, instrumentation was located in mid-slope and was considered to be unaffected.

The slope was allowed to wet up as water was introduced gradually into the basal sand layer from the top of the slope. When thoroughly wetted, the slope was frozen from the top downwards by covering the container with a refrigerated lid. An open hydraulic system was maintained during all soil freezing phases. Air temperatures were progressively lowered to around −10°C. Once the soil was frozen to its base, the water supply was shut off so that moisture content of the thawed soil was determined purely by soil ice content.

Table I. Soil properties

Soil	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	LL (%)	PL (%)	Bulk density ($kg\,m^{-3}$)	Moisture content (%)	Dry density ($kg\,m^{-3}$)
Vire	3	39	42	16	31	18	1941	26·5	1535
Feuguerolles	2	16	59	23	29	17	2034	20·7	1685

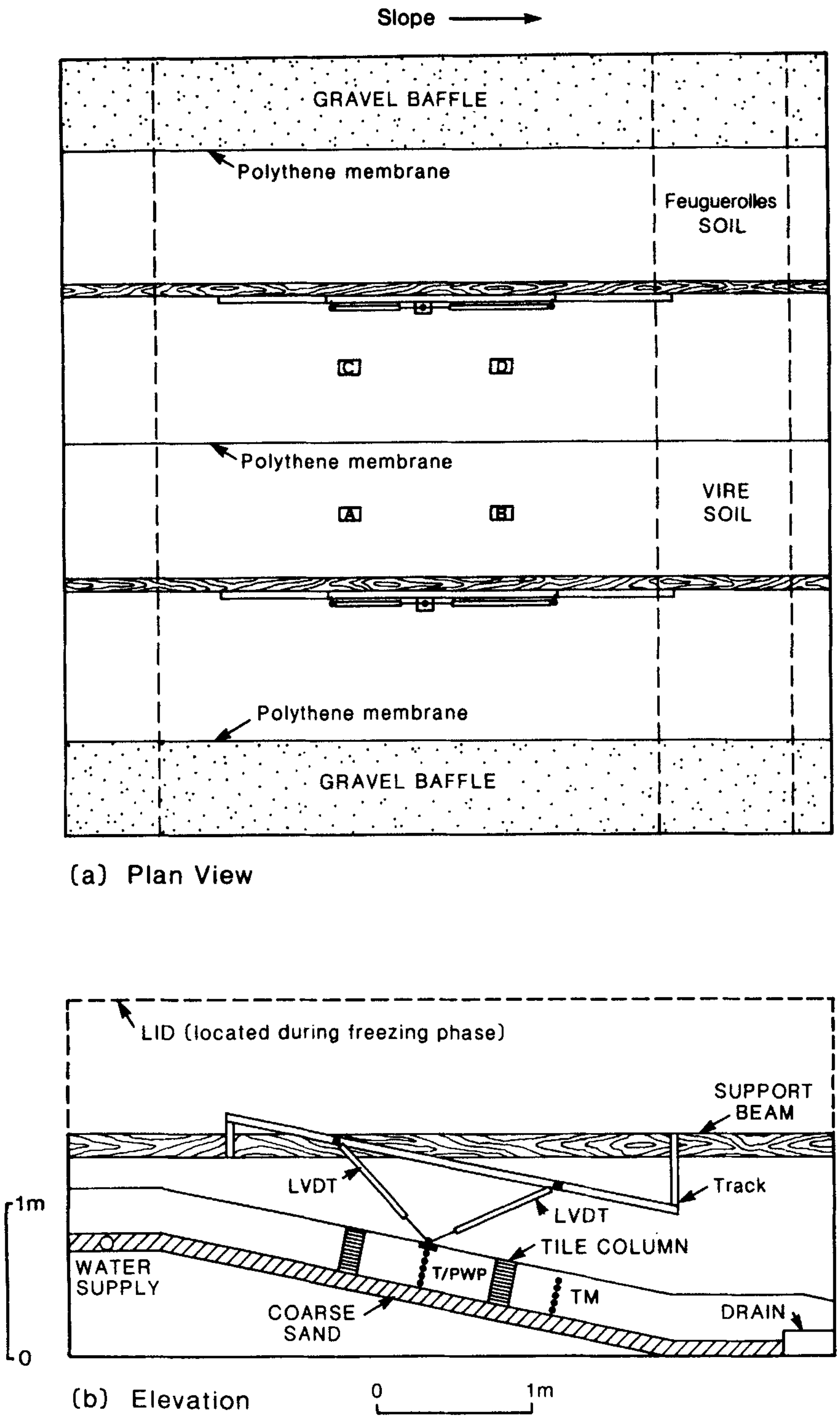

Figure 1. Diagram of apparatus: (a) plan, (b) section. Tile columns are labelled A–D. TM, thermistors; T, semiconductor temperature sensors; PWP, porewater pressure transducers

Thawing from the surface downwards was achieved by removing the refrigerated lid and allowing thaw to proceed at ambient laboratory temperatures. These varied from around 15°C in summer to 5°C in winter. The rate of thaw therefore differed in successive cycles, enabling the influence of thaw rate on slope process to be investigated.

INSTRUMENTATION

Three parameters were monitored during each freezing and thawing cycle; soil temperature, soil surface displacement, and porewater pressures. Thermistor strings measuring soil temperature were monitored with a Grant Instruments Squirrel Logger, but all other sensors were scanned by a PC-based system via an interface board and multiplexer, providing a total of 16 channels. Six channels were utilized for semiconductor temperature sensors, five for porewater pressure transducers and four for linear voltage displacement transducers, with the final channel used to monitor power supply. All instruments were logged at 30 min intervals throughout each cycle of freezing and thawing.

Temperature monitoring

Thermistor probes were installed horizontally at depths of 0, 50, 100, 150, 200 and 300 mm in each soil. Two thermistors were also set immediately above the soil surface to monitor air temperature. Soil temperatures were also monitored using temperature-sensitive semiconductor current sources. Probes were 5 mm in diameter and 40 mm in length and comprised an LM334 semiconductor in series with a 226 Ω resistor, the unit being encased in epoxy resin. A constant 5 V power supply enabled temperature monitoring via variation in current output of each sensor. Temperature sensors were installed horizontally at depths of 50, 150 and 300 mm in the slate-derived soil, and at depths of 50 and 300 mm in the mudstone-derived soil, as shown in Figure 1. Temperature measurements were accurate to within 0·2°C.

Soil surface displacement

Soil surface displacements were monitored by means of linear voltage displacement transducers (LVDTs) consisting of longstroke (300 mm) captive guided armature transducers equipped with spherical end bearings. Linearity was 0·5 per cent of full range, with temperature coefficient of 0·03 per cent full scale per °C. The configuration of LVDTs allowed measurement of soil displacement to an accuracy of ±1·5 mm over a 20°C temperature range. Two LVDTs mounted on a slotted steel strip and supported by a wooden beam formed a fixed-base triangle above each soil type (Figure 1). The apex of each LVDT triangle was connected to a perspex eye mounted on an 8 cm square perspex base plate equipped with four anchor points. The latter were buried so that the surface of the base plate was flush with the soil surface. All joints were lubricated with silicon oil to prevent seizing during the freezing process.

Frost heave during soil freezing, together with soil consolidation and downslope displacement during thaw, were quantified by the change in geometry of the fixed-base LVDT triangles. Thus, progressive frost heave and downslope soil displacement could be monitored and related to the depth of frost penetration and the depth of thaw penetration, respectively. No frost heaving of the soil surface above the footplates of the LVDT triangles was observed. The slotted steel base mounting for each pair or LVDTs was itself bolted to a 3 m long slotted steel track mounted parallel to the slope surface (Figure 1) so that at the end of each cycle of freezing and thawing, the base of each LVDT triangle could be moved downslope without disturbing the perspex plate buried in the soil surface. In this way, cumulative soil displacements could be monitored without exceeding the stroke (300 mm) of either LVDT in each triangle.

As a reference, two columns of unglazed ceramic tiles extending through the soil from the surface to the base, were installed in each experimental soil (Figure 1). Tiles were 80 mm × 40 mm × 10 mm and the coordinates of the uppermost tile in each column were recorded manually at the beginning and end of each soil freezing phase and each soil thawing phase on horizontal and vertical axes, against a benchmark on the side of the container. Excavation of the columns at the end of the freeze–thaw cycle sequence will also provide information on the distribution of downslope soil displacement with depth through the soil profile (Harris *et al.*, 1993).

Porewater pressure

In order that effective stress conditions during thaw may be analysed, it is crucial that porewater pressures be monitored in some detail. It is precisely this parameter that has been most difficult to quantify in field studies. A total of five Druck miniature pore pressure transducers (PDCR 81), each comprising a 6·4 mm diameter by 11·4 mm long stainless steel cylinder with a ceramic filter, were deployed at depths of 50, 150 and 250 mm in the slate soil (Vire), and at 50 and 250 mm in the mudstone soil (Feuguerolles) (Figure 1). Transducers were filled with antifreeze and de-aired in a vacuum desiccator prior to installation. Each transducer measured to a maximum of 350 mb with combined non-linearity and hysteresis of ±0·2 per cent Best Straight Line and thermal sensitivity of ±0·2 per cent of reading per °C.

PRELIMINARY DATA

The purpose of this paper is to provide a detailed description of the experimental design. However, some examples of instrumental output are included here to illustrate the utility of the resulting data. The experimental slope was subjected to a series of seven freezing and thawing cycles. Representative data from the second cycle (31 January–30 March) are presented below.

Soil temperature data are presented in Figure 2. Thermistor data for the Feuguerolles experimental soil are shown in Figure 2a, and semiconductor sensor data for the Vire experimental soil in Figure 2b. Note the initial progressive downward freezing and subsequent downward thawing of the soils through the

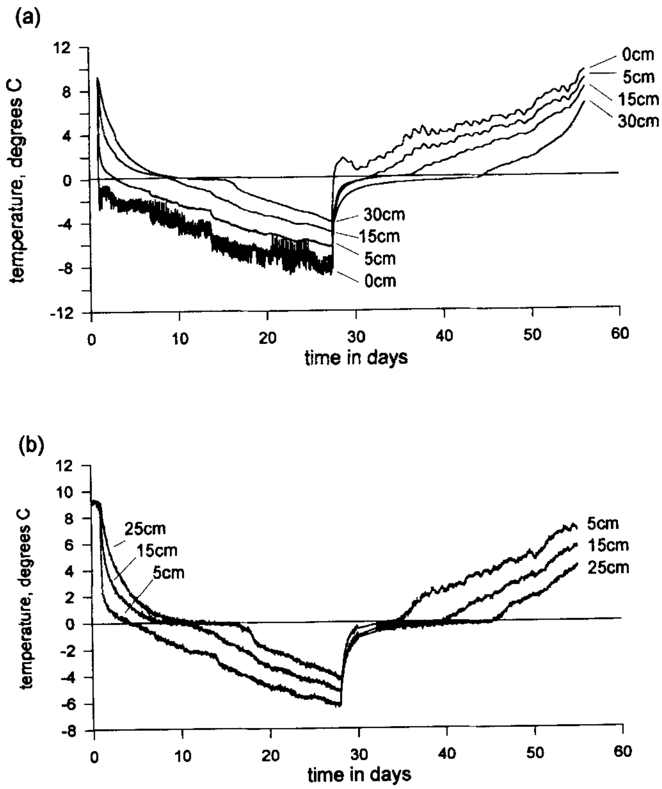

Figure 2. Temperature plots from cycle 2: (a) thermistor data from the Feuguerolles (mudstone) soil; (b) semiconductor sensor data from Vire (slate) soil. Note diurnal fluctuations in soil surface temperature in (a) and prolonged 'zero curtain' effect in (b), caused by the release of latent heat during soil freezing and absorption of latent heat during thaw

cycle. It is apparent that the 'zero curtain' effect, when soilwater freezes and latent heat is released and subsequently when soil ice thaws and latent heat is absorbed, is more marked in the finer-grained slate-derived soil (Vire) than in the mudstone soil (Feuguerolles), suggesting greater ice segregation and hence higher ice contents in the former than in the latter. This inference is supported by frost heave data recorded by the LVDTs (see below).

Surface soil displacement was measured perpendicular to the surface (frost heave and thaw consolidation) and parallel to the surface (frost creep and gelifluction). However, the perspex footplates linking the LVDT triangles to the slope surface were anchored to a depth of 20 mm. Thus, although the LVDTs accurately recorded progressive surface frost heave resulting from downward penetration of the freezing front, following initiation of each thaw phase, the footplates remained anchored in frozen soil until thaw had penetrated 20 mm below the surface, so that downslope displacement in the uppermost 20 mm of soil was not detected. Manual measurements of the coordinates of the exposed uppermost tile in each of the four tile columns (two in each soil) allowed thaw displacement of the uppermost 20 mm layer of soil to be determined and added to the LVDT data. For simplicity, however, the raw LVDT data only are presented in Figures 3 and 4.

Frost heaving during cycle 2 totalled 78 mm in the silty Vire soil but only 57·5 mm in the more sandy and gravelly Feuguerolles soil. Figure 3 illustrates the progressive heave of the soil surface during freezing and

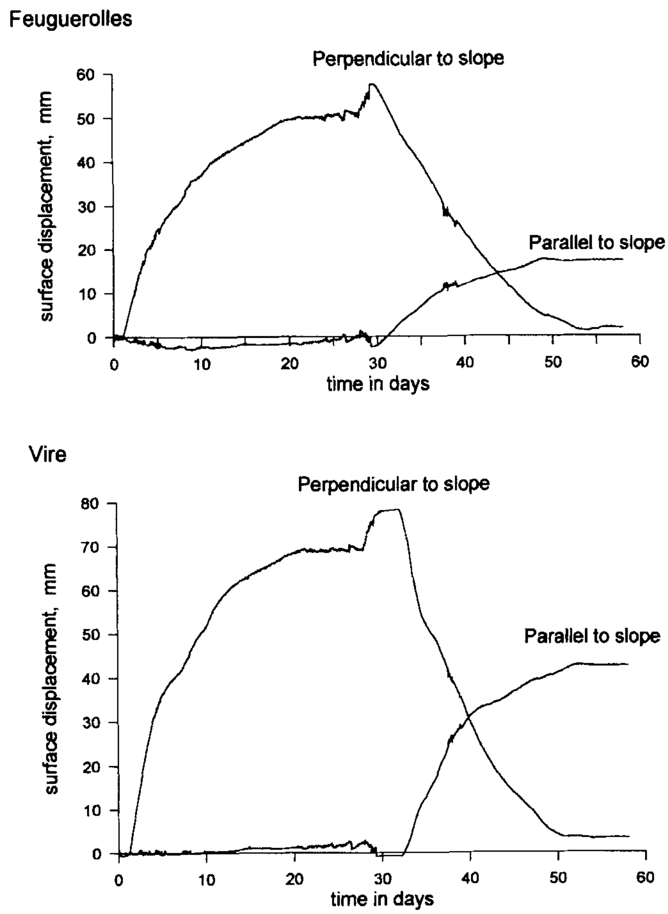

Figure 3. Soil displacement measured by LVDTs, perpendicular to the slope (frost heave) and parallel to the slope (downslope displacement). Data refer to the second of seven freeze–thaw cycles

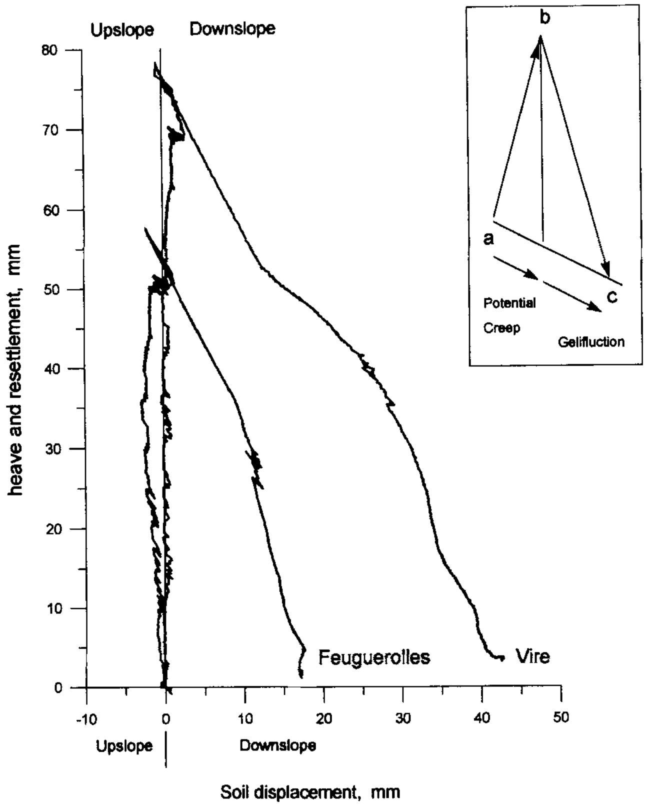

Figure 4. Vectors of soil movement during the second freezing and thawing cycle. Note that displacements were measured with respect to the slope surface (12°C gradient) so for true vectors, axes must be rotated clockwise by 12°. Inset, components of downslope displacement: potential frost creep (vertical resettlement during thaw consolidation) and gelifluction (saturated flow)

subsequent settlement during thaw, together with lateral displacements parallel to the surface. Slight upslope displacement occurred in the Feuguerolles soil during frost heaving, as shown in the soil movement vectors (Figure 4), though in the Vire soil heaving was more or less perpendicular to the surface.

Thaw consolidation resulted in recorded downslope displacements of 42·5 mm in the Vire soil and 17·2 mm in the Feuguerolles soil. Manual measurements of the surface tile in each of the tile columns suggest that a further 60 mm of downslope movement occurred in the uppermost 20 mm layer of the Vire soil (unrecorded by the LVDTs), though only 7 mm occurred in the coarser Feuguerolles soil. Similar rapid near-surface downslope thaw displacement of the Vire soil was observed in the earlier simulation experiment (Harris *et al.*, 1993, Fig. 9c, p. 302). Frost creep, if assumed to be associated with vertical soil settlement (Figure 4, inset), was responsible for some 53 per cent of total surface displacement in the Feuguerolles soil, but only 16·5 per cent in the Vire soil, the rest being accounted for by gelifluction. These differences were similar to those reported by Harris *et al.* (1993), who attributed them largely to contrasting soil granulometry. All linear measurements quoted above were recorded with an estimated error of ± 1·5 mm.

Porewater pressure is plotted here as a change in pressure relative to initial conditions at the beginning of the cycle, when the water table was at or very close to the soil surface. Transducers responded to the approach of the freezing front by registering negative pressures (tension) (Figures 5 and 6), corresponding to the cryogenic suction that causes water migration towards the freezing front (Williams and Smith, 1989). This was followed by a rapid rise in pressure once the freezing front had advanced beyond the transducer. Frozen pressures varied only slightly. Approach of the thaw zone led to a fall in recorded pore pressure. The Vire soil

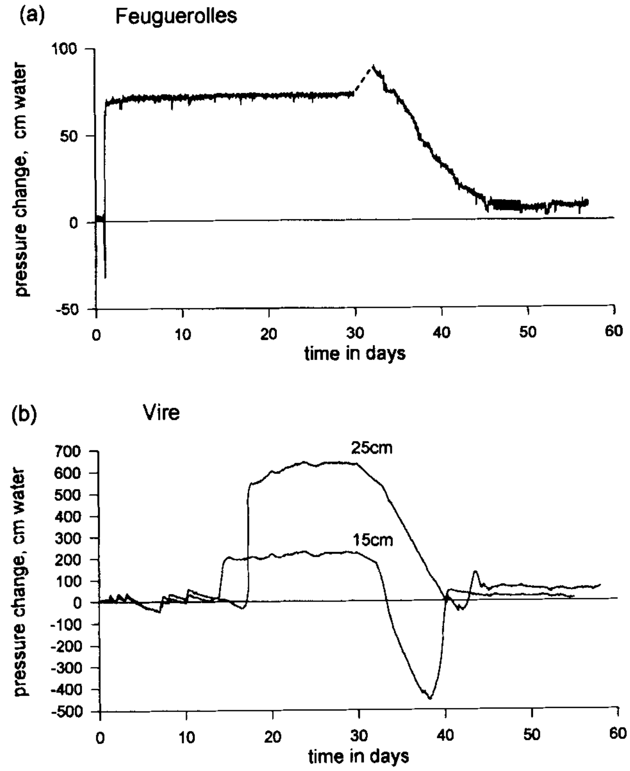

Figure 5. Change in porewater pressure recorded by Druck miniature transducers filled with antifreeze during cycle 2. (a) Feuguerolles soil, 5 cm depth; (b) Vire soil, 15 cm and 25 cm depth

transducers showed a period of negative excess pressures (tension), apparently associated with the passage of the thaw zone (there was a pronounced 'zero curtain' effect; see Figure 6), followed by a rapid rise to above initial values. In the Feuguerolles soil a similar pattern was observed, though no period of negative pressures occurred at the 50 mm depth (Figure 5a).

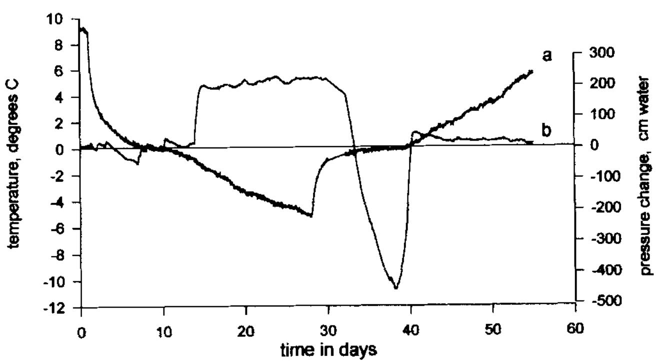

Figure 6. Relationship between (a) soil temperature and (b) porewater pressure at 15 cm depth, Vire soil, cycle 2. The frozen phase is characterized by elevated pressure readings, the thaw phase by negative pressures (suction), while immediately following thaw, water pressures rise rapidly, followed by gradual dissipation of excess pressure as soil drainage proceeds

These data suggest that soil thawing is associated with complex porewater pressure changes associated with (a) progressive phase change from soil ice to soil water and resulting reduction in volume (pressure fall), followed by (b) transfer of stress to the pore fluid (pressure rise), and finally (c) expulsion of excess porewater allowing thaw consolidation under the weight of the overburden and transfer of stress from pore fluid to soil grains (pressure fall). During the freezing phase, anticipated lowering of porewater pressure in advance of the freezing front is demonstrated, but the high frozen pressures may result from transducers within frozen soil responding to heaving pressures (total stress). Installation of load cells alongside porewater pressure transducers is planned, in order to investigate further the nature of these recorded frozen pressures.

CONCLUDING COMMENTS

Laboratory simulation of periglacial mass movement processes offers control of environmental conditions and the potential for far more detailed monitoring than is generally possible in field studies. In this paper we describe an experiment designed to measure three key parameters—soil thermal regime, frost heave and thaw consolidation—and relate these to downslope soil displacements. Resulting data will be used to refine our understanding of periglacial slope processes, improve techniques of stability analysis and provide corroborative data for numerical modelling.

REFERENCES

Coutard, J.-P., Van Vliet Lanoe, B. and Auzet, A. V. 1988. 'Frost heaving and frost creep on an experimental slope: results for soil structures and sorted stripes', *Zeitschrift fur Geomorphologie, Supplementband*, **71**, 13–23.

Harris, C. 1981. *Periglacial Mass Wasting: A Review of Research*, BGRG Research Monongraph **4**, GeoAbstracts, Norwich, 204pp.

Harris, C. 1987. 'Mechanisms of mass movement in periglacial environments' in Anderson, M. G. and Richards, K. S. (Eds), *Slope Stability*, Wiley, Chichester, 531–559.

Harris, C. 1993. 'The role of climate and soil properties in periglacial solifluction: evidence from laboratory simulation studies', in Frenzel, B. (Ed.), *Special Issue 6 European Science Foundation Project on European Palaeoclimate and Man*, Akademie der Wissenschaften und Literature Mainz, Gustav Fischer Verlag, Stuttgart, 295–308.

Harris, C., Gallop, M. and Coutard, J.-P. 1993. 'Physical modelling of gelifluction and frost creep: some results of a large-scale laboratory experiment', *Earth Surface Processes and Landforms*, **18**, 383–398.

Hutchinson, J. N. 1991. 'Periglacial and slope processes', in Foster, A., Culshaw, M. G., Cripps, J. C., Little, J. A. and Moon, C. F. (Eds), *Quaternary Engineering Geology: Proceedings of the 25th Annual Conference of the Engineering Group of the Geological Society*, Geological Society, London, 283–334.

Lewkowicz, A. G. 1988. 'Slope processes', in Clark, M. J. (Ed.), *Advances in Periglacial Geomorphology*, Wiley, Chichester, 325–370.

McRoberts, E. C. 1978. 'Slope stability in cold regions', in Andersland, O. B. and Anderson, D. M. (Eds), *Geotechnical Engineering for Cold Regions*, McGraw-Hill, New York, 363–404.

Morgenstern, N. R. and Nixon, J. F. 1971. 'One-dimensional consolidation of thawing soils', *Canadian Geotechnical Journal*, **11**, 447–469.

Rein, R. G. and Burrous, C. M. 1980. 'Laboratory measurements of subsurface displacements during thaw of low-angled slopes of a frost susceptible soil', *Arctic and Alpine Research*, **12**, 349–358.

Smith, D. J. 1988. 'Rates and controls of soil movement on a solifluction slope in the Mount Rae area, southern Canadian Rocky Mountains', *Zeitschrift fur Geomorphologie, Supplementband*, **71**, 25–44.

Williams, P. J. and Smith, M. W. 1989. *The Frozen Earth*, Cambridge University Press, Cambridge, 306pp.

Washburn, A. L. 1979. *Geocryology*, Edward Arnold, London, 416pp.